187. Gaia synthetic photometry

A RECENT PAPER by Montegriffo et al. (2023b) is titled *'Gaia DR3. The Galaxy in your preferred colours: Synthetic photometry from Gaia low-resolution spectra'*. It is an important contribution to Gaia's science. It runs to 59 pages, and containing many details. But it is well summarised by the first two sentences of the abstract.

> *'Gaia DR3 provides novel flux-calibrated low-resolution spectrophotometry for 220 million sources in the wavelength range 330–1050 nm. Synthetic photometry directly tied to a flux in physical units can be obtained from these spectra for any passband fully enclosed in this wavelength range.'*

ANYONE who has worked with photometric standards, or has had to convert observations to absolute flux, will know how important, yet how subtle and complex, such work can be. Montegriffo et al. (2023b) provide the tools to convert Gaia photometry to any other photometric system, subject to a couple of obvious caveats.

Suppose that you have several years of Sloan Digital Sky Survey photometry in its five photometric bands (u, g, r, i, z), and you want to extend the time series using the Gaia data. Or you want to transform the Gaia photometry to the systems used by Pan-STARRS or the Vera C. Rubin Observatory. This can now be done!

GAIA OBSERVES in three bands. The main astrometric field, G, maximises photon throughput, and spans 330–1050 nm, defined by mirror reflectivities and the CCDs. The BP and RP data (together referred to as XP) are acquired as low-resolution spectra ($\lambda/\Delta\lambda \simeq 25-100$) over 330–680 nm and 640–1050 nm respectively. They have been subject to an extensive validation (De Angeli et al., 2023), and internal/external calibration (Carrasco et al., 2021; Montegriffo et al., 2023a).

Gaia's all-sky, multi-epoch measurements yield photometry which rivals the best available. Gaia DR3, from 2022, provides mean G magnitudes for 1.8 billion sources, and mean $G_{\rm BP}$ and $G_{\rm RP}$ photometry for 1.5 billion, typically at sub-millimag precision. Mean BP and RP *spectra* are provided for 220 million sources, mostly with $G < 17.5$ mag. The final data release, DR5, foreseen around 2030, will extend this to all 2–3 billion sources.

LET ME GIVE some background to the design of the low-resolution spectra for reasons that will become clear later. The acquisition of multi-colour photometry in parallel with the astrometric observations was a design goal from the earliest days of Gaia, and was originally foreseen (and extensively optimised) as a set of (eventually 19) broad- and narrow-band filters (Jordi et al., 2006). As I described in essay 68, and at a rather late satellite design stage, the dedicated photometric telescope with its associated filters was exchanged for two fused silica prisms which disperse the light entering the main telescope's two fields of view.

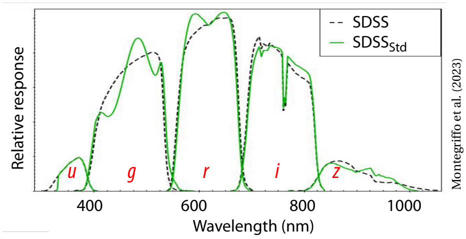
Their resolution, which matched the earlier filter design, results from the intrinsic dispersion of fused silica, and varies from 3–27 nm per pixel over 330–680 nm for BP, and from 7–15 nm per pixel over 640–1050 nm for RP.

SYNTHETIC PHOTOMETRY, as derived from observed spectrophotometry, is based on the computation of a normalised mean flux obtained by integrating the product of a transmission curve, $S(\lambda)$, and a spectral energy distribution over a given wavelength (or frequency) interval, depending on the adopted photometric system (e.g. Bessell, 2005). It can be used to provide colours within standard systems, for insights into the spectra or colours of unusual stars or stellar systems, for the validation or re-calibration of existing photometric surveys, and *'the opportunity to experiment with the performance of a photometric system on a huge data set of real data on real sources before its actual realisation'*.

In the Gaia archive, the XP spectra are stored as the coefficients (and their covariances) of a set of orthogonal basis functions, from which the spectral energy distributions can be reconstructed (De Angeli et al., 2023; Montegriffo et al., 2023a).

A KEY STEP in the derivation of the XP synthetic photometry, described in detail by Montegriffo et al. (2023b, §2.2), is 'standardisation'. For Gaia, this compensates any systematics present in the externally calibrated XP spectra by 'tweaking' the Gaia transmission curve to minimise any residual magnitude or colour differences.

The example below shows the Sloan Digital Sky Survey transmission curves (Doi et al., 2010, black dashed line), and their 'tweaked' version, obtained with the standardisation process, as the green continuous lines. I stress that the green lines do *not* indicate some improved estimation of the SDSS filter profiles, but rather reflect empirical adjustments which correct for the systematic errors that still affect the externally calibrated XP spectra.



In principle, such synthetic photometry can be obtained from the calibrated XP spectra in any photometric system subject to two constraints: that the target passband must (of course) be enclosed within the spectral range covered by Gaia's XP spectra (330–1050 nm), and that the passband's characteristic width exceeds the 'line-spread function' of the XP spectra at the relevant wavelength.

THEY THEN detail a number of important photometric systems which they have reconstructed from the Gaia XP-derived synthetic photometry. Their general conclusions are that existing high-quality photometry can be reproduced within a few per cent over a wide range of magnitudes and colour, for wide and medium bands, and with around milli-mag accuracy.

For example, in their earlier paper detailing the external calibration of the XP spectra, Montegriffo et al. (2023a, §8.4.2) showed that the Hipparcos H_p, B_T, and V_T photometry, recognised as a benchmark of excellent precision by Bessell (2005), are all reproduced by the XP synthetic photometry to better than 2.5 milli-mag.

Montegriffo et al. (2023b) then detail and demonstrate performances for various wide-band systems, including the Sloan Digital Sky Survey, the Johnson–Kron–Cousins system, and the PanSTARRS and HST systems.

Amongst narrow-band photometric systems, they detail results for the Strömgren system (widely used for the determination of effective temperature and surface gravity), the Javalambre J–PAS and J–PLUS surveys, and the IPHAS Hα emission-line survey.

WITH MY LONG involvement in the preparation of the Gaia photometric system, I was particularly fascinated by one of their specific examples: replicating the proposed photometric *filter* system which I referred to earlier: the set of broad- (C1B) and medium-band (C1M) filters, carefully designed by Jordi et al. (2006) to maximise the scientific return in terms of $T_{\rm eff}$, metallicity, gravity, reddening, and even α-element abundances.

To investigate how the system would have performed, Montegriffo et al. (2023b, §4.4) reconstructed the C1 colour indices, and showed that they could, indeed, clearly separate giant and main sequence stars in the $\log g$ versus $T_{\rm eff}$ plane (their Fig. 22), and could pick out both the white dwarf sequences, and the 'Jao gap' (essay 152) in the various colour–magnitude diagrams.

THEY ILLUSTRATE several other scientific applications, including the detection of multiple populations in globular clusters, metallicity derived in the Strömgren system, metallicity estimation for very metal-poor stars, and the classification of emission-line sources.

And to make this synthetic photometry more readily accessible, they provide two derived catalogues.

The first is the Gaia Synthetic Photometry Catalogue (GSPC), which includes the majority of the 220 million stars with XP spectra released in Gaia DR3, in 13 passbands, including UBVRI in the JKC system, *ugriz* in the SDSS system, and two in the HST–ACS/WFC system.

The other is the Gaia Synthetic Photometry Catalogue for White Dwarfs (GSPC–WD), comprising 100 000 white dwarfs with DA/non-DA classification, obtained with a Random Forest (machine-learning) algorithm.

PRE-DATING the synthetic photometry, Gaia photometry was already being used to correct other photometric surveys. The 6-colour zero-points of ANU's SkyMapper Southern Survey (SMSS), had already been anchored to Gaia DR2 (Huang et al., 2021). Pancino et al. (2022) used Gaia EDR3 to recalibrate 200 000 secondary standards in the Johnson–Kron–Cousins system.

Huang et al. (2024) describe independent efforts to correct residual systematics in the Gaia DR3 XP spectra using external spectral libraries including CALSPEC, Hubble's NGSL, and LAMOST DR7.

Amongst work already making use of the GSPC, Zhou et al. (2023) used the DR3 synthetic photometry to correct patterns in the DESI (Dark Energy Spectroscopic Instrument) Legacy Imaging Surveys. Anderson et al. (2024) derived corrections for their OGLE variables in their measurement of TRGB magnitudes.

López-Sanjuan et al. (2024) used the catalogue to recalibrate the 12 passbands of the Javalambre Photometric Local Universe Survey (J–PLUS) third data release.

Xiao et al. (2024) undertook a comprehensive recalibration of narrow-, medium- and broad-band photometry from the Southern Photometric Local Universe Survey (S–PLUS) using the Gaia synthetic photometry.

THE LOW-RESOLUTION BP and RP spectral data are described by De Angeli et al. (2023) as *'one of the exciting new products in Gaia Data Release 3'*. Montegriffo et al. (2023b) suggest that the availability of the derived synthetic photometry may constitute *'a true revolution in optical photometry'*. We can let future users decide!